A Direct Simulation-Based Study of Radiance in a Dynamic Ocean

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Award Number: N00014-06-1-0073

LONG-TERM GOAL

The primary focus of this research is to integrate dynamical processes of wave and turbulence in the upper ocean surface boundary layer (SBL) into a physics-based computational capability for the time-dependent radiative transfer (RT) in the ocean. The combined capability we develop will provide direct forward predictions of the radiance distributions in the upper ocean. We aim to use this capability for understanding the basic features and dependencies of oceanic radiance on the wave environment, to provide guidance and cross-calibration for field measurements, and to validate and benchmark existing and new theories. As an ultimate goal, the proposed direct simulation also provides a framework, in conjunction with sensed radiance data, for the optimal reconstruction of salient features of the ocean surface and the above-water scene.

OBJECTIVES

This project is part of the modeling effort in the Radiance in a Dynamic Ocean (RaDyO) DRI. The scientific and technical objectives of our research are to:

- develop numerical capabilities for the direct simulation of nonlinear capillary-gravity waves (CGW) with the inclusion of wave breaking dissipation, energy input by wind, and surfactant effects
- develop numerical capabilities for free-surface turbulence (FST) and resultant surface roughness
- develop bubble transport simulation in CGW-FST field, with bubble source models using simulations of steep breaking waves and measurement data
- develop direct simulations of RT in the presence of SBL processes of wave, turbulence, and bubbles
- obtain validations and cross-calibrations against field measurements
- use numerical tools of forward prediction to understand and characterize the radiance distribution in terms of the SBL dynamical processes, and to parameterize and model radiance transport and distributions

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2007	**Annual**	**00-00-2007 to 00-00-2007**

4. TITLE AND SUBTITLE
A Direct Simulation-Based Study Of Radiance In A Dynamic Ocean

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Johns Hopkins University,Department of Civil Engineering,Baltimore,MD,21218

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

- develop inverse modeling for the reconstruction of free-surface properties and objects using measured RT data and direct simulation

APPROACH

We develop a simulation approach based on direct physics-based simulations and modeling to solve the problem of ocean RT in a dynamic SBL environment that includes CGW, FST roughness, wave breaking and bubble generation and transport. The complex dynamic processes of the ocean SBL, the nonlinear CGW interactions, the development and transport of FST, and the generation and transport of bubbles are modeled using physics-based computations. The modeling of these hydrodynamic processes is coupled with the computation of radiative transfer.

For the nonlinear gravity-capillary wavefield evolution, we employ an efficient phase-resolved computational approach. With this approach, we obtain detailed spatial and temporal information of the wavefield during its nonlinear evolution. This computational tool is based on an efficient high-order spectral (HOS) method that we developed for direct simulations of nonlinear gravity wavefield evolution. HOS is a pseudo-spectral method developed based on the Zakharov equation and mode-coupling idea. Using direct efficient HOS computations and sensed wave data, we can obtain a phase-resolved reconstruction of nonlinear wavefield evolution based on multi-layer optimizations. With this highly efficient approach, we expect to capture realistic ocean gravity and capillary wavefield that has a wide range of length scales.

In addition to CGW, radiative transfer at ocean surface is also affected by surface roughness associated with FST. In this study, for moderate wave amplitudes, the FST field is obtained from simulation of the Navier-Stokes equations on a boundary-fitted grid subject to the fully-nonlinear free-surface boundary conditions. When waves steepen and break, an interface capturing method on fixed Eulerian grids is used, with which the air and water together are treated as a system with varying density, viscosity, and diffusivity. Effects of surfactants can be captured through the Plateau-Marangoni-Gibbs effect for which we perform direct simulation of the surfactant transport in the free-surface flow, which is in turn affected by the surfactant-laden boundary conditions. To capture the interaction between FST and CGW, we will perform FST simulations with realistic wave inputs obtained from the HOS CGW simulations.

The high-resolution mapping of the free-surface deformation from our direct CGW and FST calculations is coupled into the computation of the underwater radiance field. As light enters the water from the air, they are modified in both propagation direction and intensity at the sea surface subject to Snell's law and Fresnel transmission. The propagation of radiance in the sea water is captured by simulation of radiative transport subject to absorption and multiple scattering. In this study we perform direct simulations of RT in a three-dimensional, temporally-evolving, upper-ocean environment with the key SBL processes being directly simulated. We will first focus on a Monte Carlo simulation of photons while other techniques for the direct simulation of radiance will be investigated at a later stage of this project. In order to capture radiative scattering by bubbles which are generated by wave breaking, we first simulate transport of bubbles by tracking Lagrangian trajectories and by computations with an Eulerian multi-phase fluid modeling. Based on the simulated locations and populations of bubbles with various size distributions, scattering of radiance is solved numerically using the radiative scattering result of individual bubbles obtained with the Mie theory.

Large-scale high-performance computation on parallel computers is used to meet the computational challenges in the CGW, FST, and RT simulations. The suite of codes developed for this research is parallelized using massage passing interface (MPI) based on domain decomposition.

WORK COMPLETED

During the fiscal year of 2006, substantial progresses have been made including:

- Development of an advanced numerical method for turbulence-wave interaction, in which turbulence is generated by a novel random force method while wave is generated by surface pressure.

- Further development and improvement of our Monte Carlo simulation tool for RT in the upper-ocean wave and turbulence field.

- Establishment of an extensive simulation database for wave-turbulence interaction, based on which substantial understanding on the physics of wave-turbulence interaction has been obtained. Using the surface geometry obtained from wave-turbulence simulation, a large set of RT simulations has been performed to obtain instantaneous, three-dimensional radiance field underwater.

- Elucidation of the dependence of surface geometry on turbulence and waves, and the resultant effects on underwater radiance transfer. Investigation of characteristics of underwater irradiance distribution in relation to free-surface geometry and roughness has been performed. Correlation between underwater irradiance distribution and flow structures has been quantified.

- Preliminary study of reverse modeling. Based on the underwater radiance field, we developed a ray tracing method to reconstruct water surface topography. We investigated the dependence of surface reconstruction accuracy on the depth of underwater radiance field data and the accuracy of surface reconstruction for surface features at different scales.

RESULTS

Radiative transfer across the air-sea interface is governed by the interface slope, which is highly dependent on the interaction of waves with turbulence. In this study, we developed a novel simulation approach for wave-turbulence interactions. For turbulence generation, we extended the random force method to the free-surface turbulence case, which has the advantage of eliminating artificial bottom effects existing in previous free-surface turbulence simulation study in the community. For water wave generation, we developed and tested an approach using surface pressure spatial and temporal variations. The above developments will potentially enable us to simulate more realistic wave and turbulence field to match experiment conditions. A typical simulation result is plotted in Figure 1, which shows the water surface geometry and the underwater downwelling irradiance field at various depths.

We have obtained extensive datasets for ocean turbulence with various wave conditions and the associated surface topography. Figure 2 shows an example of turbulence velocity and vorticity fluctuations as a function of depth. As the free surface is approached, the horizontal velocity component increases at the expense of vertical velocity. This variation is caused by the blockage effect of the water surface on fluid motions. Close to the surface, the horizontal vorticity component attenuates sharply, due to the dynamic shear stress boundary condition at the water surface. The above results show clearly a two-layer structure in the flow field.

The water surface evolves in response to the action of fluid motions in forms of waves and surface roughness. In this study, we investigated the surface deformation for a wide range of Froude and Weber numbers. Representative results are shown in Figure 3 in terms of surface elevation spectra. As expected, the presence of surface tension has a strong effect on high wave-numbers, i.e. capillary waves. As the Froude number increases, potential energy is transferred from low wave numbers to high wave numbers.

With the water surface deformation calculated, RT simulation is performed by a Monte Carlo method. We consider vertical light beams propagating through the ocean surface subject to Snell's law and Fresnel transmission. The propagation of radiance in the sea water is captured by simulation of radiative transfer subject to absorption and multiple scattering. Figure 1 shows the downwelling irradiance distribution at representative depths. The focusing and defocusing effect of the water surface deformation as well as the attenuation of radiance intensity with depth are clearly shown. Spectrum of downwelling irradiance as a function of depth is shown in the contour plot in Figure 4 (the zero mode, i.e. mean downwelling irradiance value, is not plotted). Figure 4 illustrates the distribution of irradiance at different scales corresponding to the spectrum of surface deformation (Figure 3).

We also started the study on reverse modeling and have obtained encouraging results. We developed a ray tracing approach for the reconstruction of water surface based on underwater radiance field. Figure 5 and Figure 6 show sample results. It is found that the depth of radiance data plays an important role in the reverse modeling. If data very close to the surface are used, large-scale (horizontal) surface structures may not be captured, since it needs sufficient depth for the focusing/defocusing effects of large surface deformation to show. On the other hand, if radiance data in deep regions are used, many of the small-scale surface features may be missing. Figures 5 and Figure 6 show that there exists an optimum depth for water surface reconstruction.

The above observation on the accuracy of reverse modeling can be quantified via the comparison of the spectra of water surface deformations plotted in Figure 7. For the intermediate depth case, the good agreement of the reconstructed surface with the original surface at all of the wave numbers is quite encouraging. It should be pointed out, however, that the study on the inverse problem is still at an early stage. Results shown in Figures 5 to 7 are for relatively small surface deformations (for the case of strong underwater turbulence interacting with the free surface, the maximum surface steepness is $21°$; for the wave-turbulence interaction case, the incident wave has a slope of $ka = 0.05$). As the surface becomes steeper, higher order nonlinearity in the reconstruction and optimization process must be considered. For the incorporation of and comparison to measurement data in the coming years of this DRI, substantial development in data assimilation is also needed. These developments are among the topics of our ongoing research.

IMPACT/APPLICATION

This study aims to obtain a fundamental understanding of time-dependent oceanic radiance distribution in relation to dynamic SBL processes. Our work is intended as part of an overall coordinated effort involving experimentalists and modelers. The simulation capabilities developed in our research will provide experimentalists with a powerful tool to validate the observation data. The simulation tool is expected to provide some guidance for field measurement planning. The simulation can also provide whole-field (spatial and temporal) data that helps the interpretation of sparse observation datasets. From simulation, some physical quantities that are difficult to measure can be obtained. What is also significant is that the simulation can be used as a useful tool to isolate physical processes that are coherent in the natural environment. With such analysis, improved understanding, modeling and parameterizations of dependencies of oceanic radiance on SBL environment will be obtained. Our ultimate goal is to use the forward modeling capabilities resulted from this project as a framework for inverse modeling and reconstruction of ocean surface and above water features based on sensed underwater radiance data.

TRANSITIONS

The numerical datasets obtained from this project will provide useful information on physical quantities difficult to measure. Simulations in this study will provide guidance, cross-calibrations and validations for the experiments. They also provide a framework and a physical basis for the parameterization of oceanic radiative transfer in relation to dynamic surface boundary layer processes.

RELATED PROJECTS

This project is part of the ONR-sponsored Radiance in a Dynamic Ocean (RaDyO) DRI (http://www.opl.ucsb.edu/radyo). Our study is performed jointly with Professor Dick K.P. Yue's group at MIT and is in close collaboration with other investigators in this DRI.

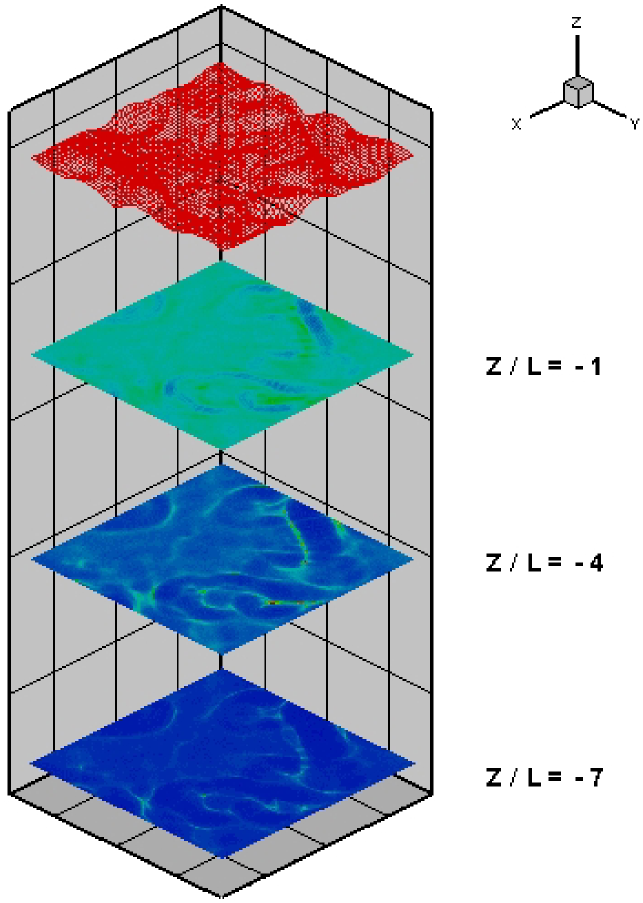

Figure 1. Free-surface deformation and contours of the downwelling irradiance at various depths (normalized by characteristic turbulence length scale comparable to the integral scale).

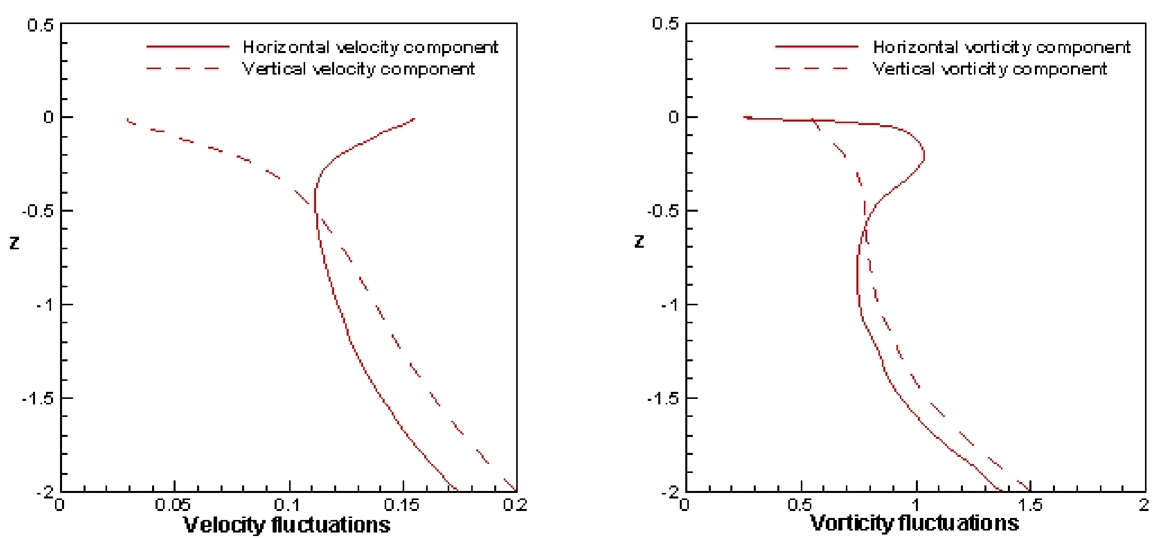

Figure 2. Vertical profiles of turbulence velocity and vorticity fluctuations for horizontal and vertical components.

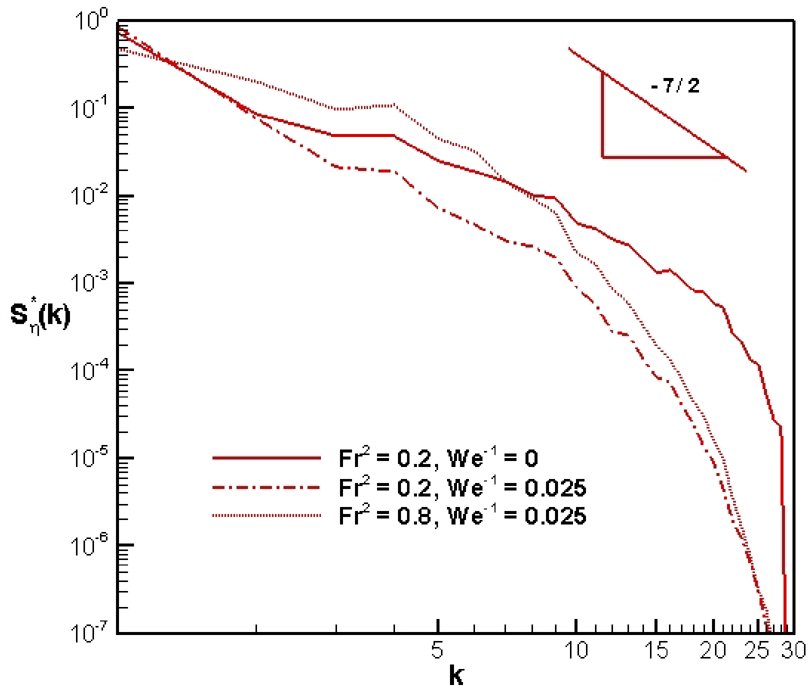

Figure 3. Spectra of surface roughness for free-surface turbulent flows with representative Froude and Weber numbers. The spectra are normalized by the r.m.s. value of surface elevation.

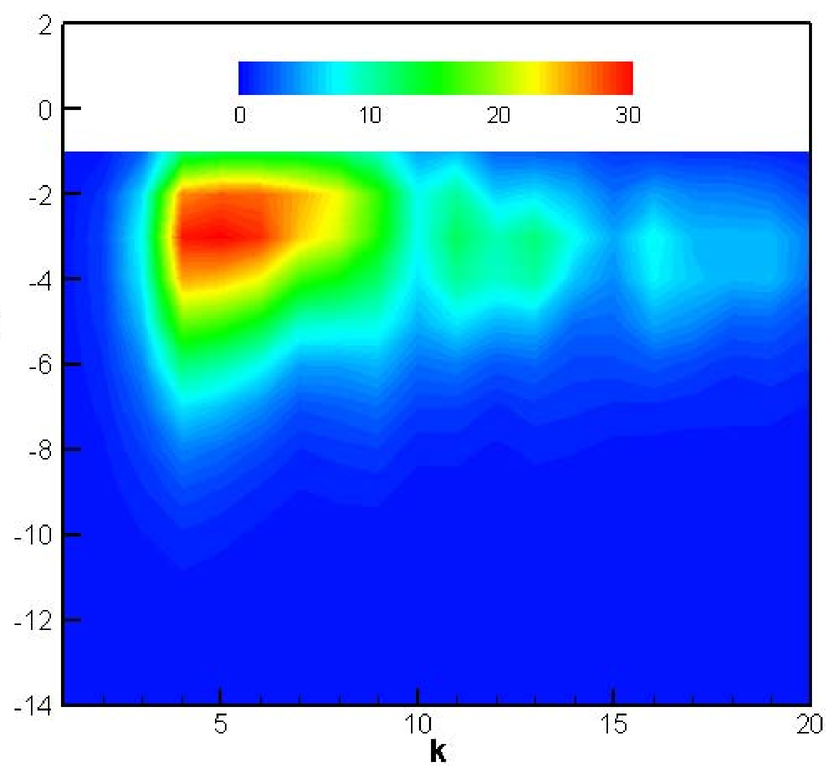

Figure 4. Spectra of irradiance field as a function of depth. The spectra are normalized by the local irradiance values. The spectral values at k=0 are not shown.

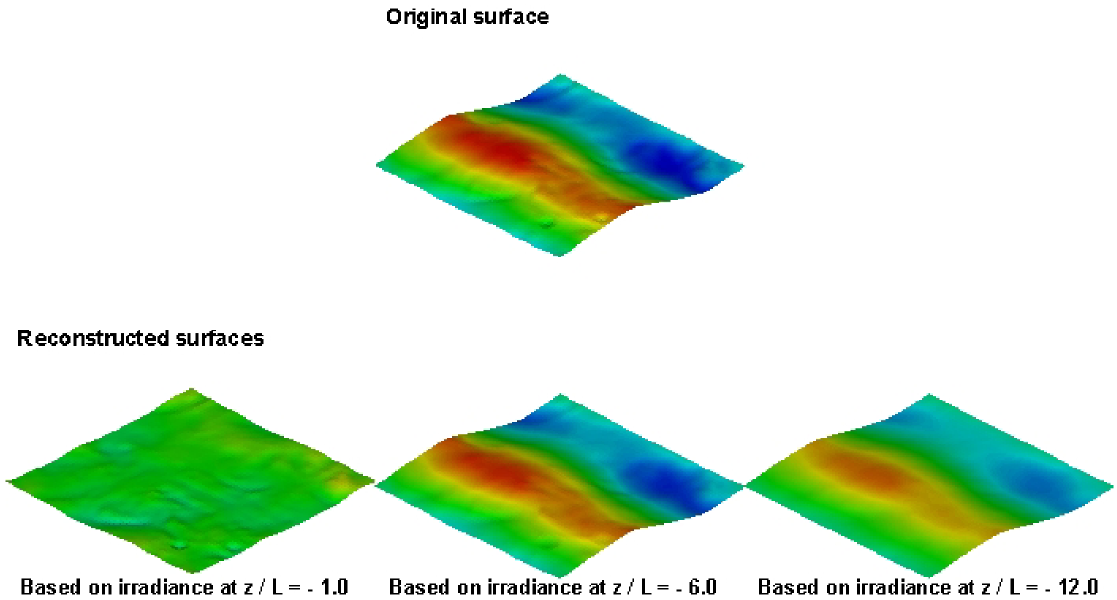

Figure 5. Reconstruction of water surface geometry based on underwater irradiance field for the case of a dominant wave interacting with ocean turbulence. Comparison of the original surface with constructed surfaces using radiance data at various depths is shown. Contours represent surface elevations.

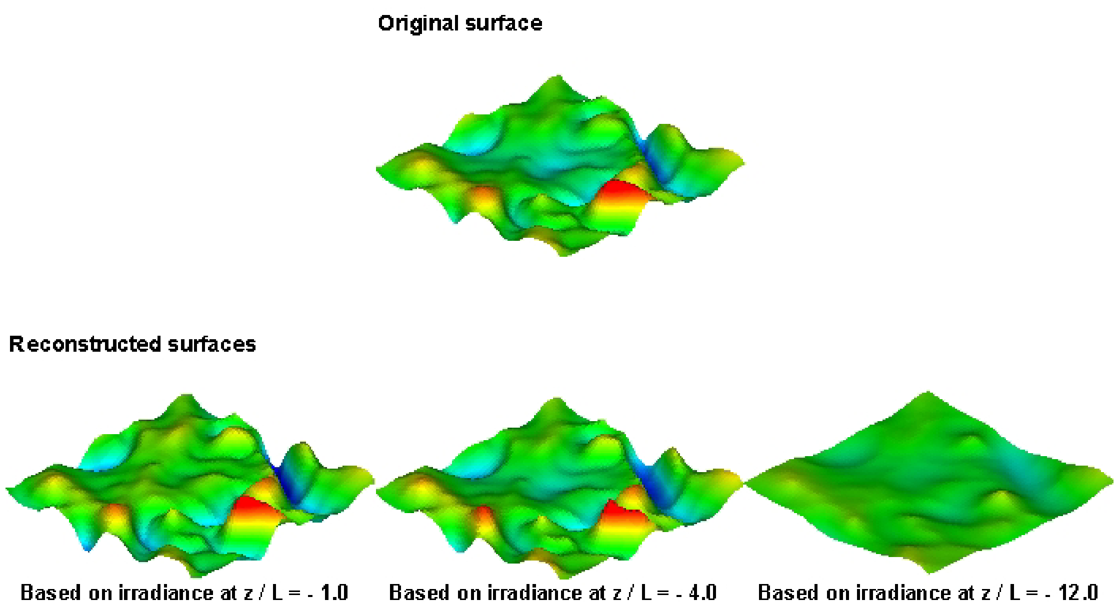

Figure 6. Reconstruction of water surface geometry based on underwater irradiance field for the case of strong underwater turbulence interacting with water surface. Comparison of the original surface with constructed surfaces using radiance data at various depths is shown. Contours represent surface elevations.

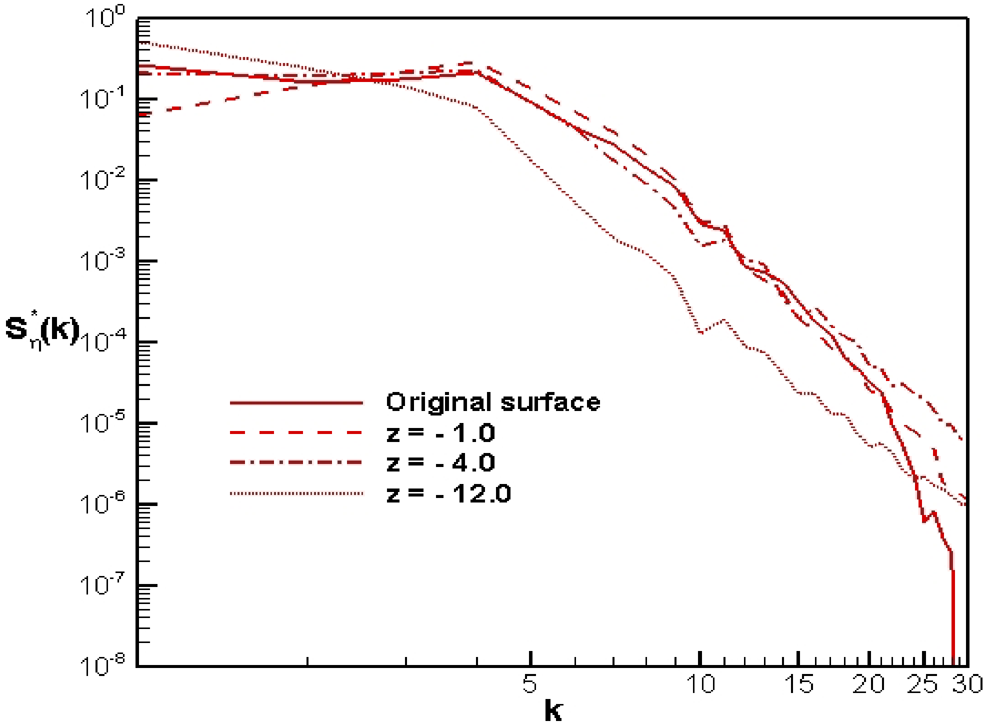

Figure 7. Spectra of water surface roughness for the case of strong underwater turbulence interacting with water surface. The spectra are normalized by the r.m.s. values of surface elevations. Comparison of the original surface with constructed surfaces using radiance data at various depths is shown.